A SIMULATION STUDY ON A CATHETER NAVIGATION METHOD FOR GUIDING THE ABLATIVE THERAPY OF CARDIAC ARRHYTHMIAS

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Abstract-**We investigated the ability of a computer algorithm to guide the ablative therapy of cardiac arrhythmias. Specifically, in computer simulations we examined the accuracy of this algorithm to guide the tip of the ablation catheter to the site of the origin of the arrhythmias. We model both the ECG corresponding site of the origin of the arrhythmia and current pulses generated from a pair of electrodes at the tip of the ablation catheter with a single equivalent moving dipole (SEMD). In the forward problem we employed a realistic anatomic geometry torso model. In the inverse problem we used the SEMD model in an infinite homogeneous volume conductor. The results of this investigation suggest that the bounded, heterogeneous volume conductor introduces systematic error in the estimated compared to the true dipole position. However, we found that the systematic error had minor influence in the ability of the algorithm to accurately guide the tip of the ablation catheter to the site of the origin of the arrhythmia.**
***Keywords* – Ablation, cardiac arrhythmias, catheter navigation, inverse problem, body surface potentials, dipole**

I. INTRODUCTION

We have previously presented an inverse algorithm that allows us to fit potentials due to an arbitrary bioelectric source to a single equivalent moving dipole (SEMD) model [1]-[3]. In this algorithm, we achieve fast identification of the SEMD parameters, by employing a dipole model in an infinite homogeneous volume conductor and ignoring distortions due to the bounded, heterogeneous volume conductor. We have demonstrated that these SEMD parameters for each point during the cardiac cycle provided reconstructed potentials that were highly correlated with the measured ECGs at the same sites [1] and accurately identified spatially separated epicardial sources [2]. We have also investigated the effect of measurement noise, as well as dipole position and orientation in the accuracy of the inverse algorithm to obtain the SEMD parameters in a bounded, heterogeneous volume conductor [3]. In that study [3], the dipole position had the most significant effect on the accuracy of the algorithm and measurement noise did not appear to have a significant influence in identifying the SEMD parameters. The results of this study also suggested that the use of the SEMD model in an infinite homogeneous volume conductor introduced an offset in the estimated dipole position compared to the true one.

In the present study, we investigate the ability of this algorithm in accurately guiding the ablative therapy of cardiac arrhythmias. To accomplish this we model both the site of the origin of the arrhythmia and current pulses generated from a pair of electrodes at the tip of the ablation catheter with a SEMD and we use a realistic anatomic geometry torso model and the boundary element method (BEM) [4]-[5] to calculate the resulting body surface potentials. In the inverse problem the algorithm to estimate the SEMD parameters is used. We seek to examine the effect of the systematic error when trying to superpose the dipole due to the catheter tip to the dipole due to the site of the origin of the arrhythmia.

II. METHODS

A. Forward Problem Calculation Using the BEM

In the present study we calculate the potential distribution (*forward problem*) at the outer surface of a volume conductor generated by a dipole of known position, strength and orientation using the BEM [4]-[5]. In the BEM, the properties of the volume conductor model are approximated by realistically shaped compartments of homogeneous conductivities. We have constructed a realistic three-dimensional (3-D) volume conductor model of the torso from magnetic resonance imaging (MRI) data sets. Furthermore, the BEM requires triangular descriptions of the boundary surfaces of the compartments. The model used in this study is consisted of torso (490 triangles), heart (1148 triangles) and lungs (504 triangles) and is shown in Fig 1 (b). The triangular descriptions of the torso, heart and lungs are shown in Fig 1. The figure also shows 49 (out of 64) electrode positions in (a). The conductivities within the torso, the heart and the lungs were 0.20, 0.23 and 0.04 S/m, respectively. Finally, the body surface potential distribution at 64 electrode positions generated by a dipole in the heart was calculated employing the BEM.

B. Inverse Problem Estimation Using the SEMD

In the *inverse problem* estimation, we employ the SEMD model embedded in an infinite homogeneous volume conductor. Then, the potential ϕ^i at position $\mathbf{r}^i$ on the body surface due to a dipole at $\mathbf{r}'$ with moment $\mathbf{p}$ is given by

$$\phi^i(\mathbf{r}', \mathbf{p}) = \mathbf{p} \cdot (\mathbf{r}^i - \mathbf{r}') / |\mathbf{r}^i - \mathbf{r}'|^3 \qquad (1)$$

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Finally, the SEMD parameter estimates (**r**', **p**) are obtained using our inverse algorithm that minimized the χ^2/dof:

$$\chi^2/\mathrm{dof} = (1/\mathrm{dof}) \sum_{i=1}^{I} (\phi^i - \phi^i{}_m)/\, \sigma^i, \ \mathrm{dof} = I - 6 \qquad (2)$$

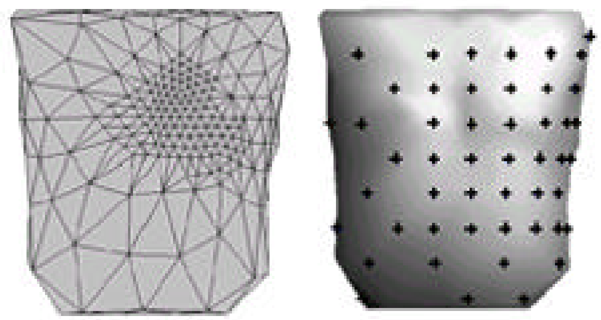
where $\phi^i{}_m$ is the measured body surface potential at position i due to the point dipole calculated using the BEM, σ^i is an estimate of the electrode noise, and I is the number of the electrodes. We use the Simplex method to perform the minimization by searching in position (**r**') space, with the unique optimal values of **p** at each **r**' obtained by solving a set of three linear equations ($\partial(\chi^2/\mathrm{dof})/\partial p_j=0$, j=1,2,3). We use a predefined random number of initial position seeds and the Simplex is deemed to converge when the minimized χ^2/dof for two seeds (out of ten total) yielded dipole positions less than 5 mm apart. The optimal solution is then chosen to be the solution with the lower χ^2/dof.

C. Catheter Navigation Simulation

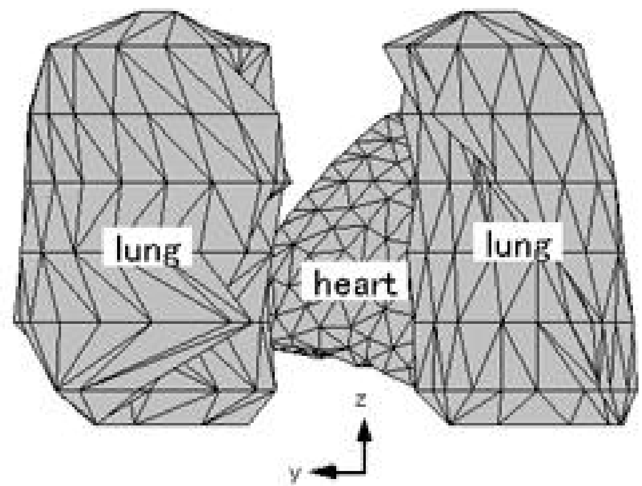
To analyze the influence of the systematic error during the catheter navigation, when trying to superpose the dipole due to the catheter tip to the dipole due to the site of the origin of the arrhythmia, we conducted the following simulation. We modeled both the site of the origin of the arrhythmia and current pulses generated from a pair of electrodes at the tip of the ablation catheter with a SEMD. So, we placed one dipole at the position of the site of the origin of the arrhythmia and another one at the tip of the catheter (we assumed that the orientation of the catheter was the same with the dipole at the tip).

The BEM is used to calculate the resulting body surface potentials due to both dipoles: the one at the site of the origin of the arrhythmia and the tip of the ablation catheter. For the sake of simplicity, no measurement noise is introduced. In the inverse problem the algorithm to estimate the SEMD parameters is used.

A dipole of magnitude 0.82 Vmm^2 is placed in one of the ventricles and served as the target site (the site of the origin of the arrhythmia) during the catheter navigation. Then, the dipole at the catheter tip is introduced in the same ventricle in which the target dipole is placed. The position of the tip of the catheter is defined to be the initial point of the navigation process while the orientation of the catheter tip, i.e. of the dipole moment components at the tip, is randomly chosen. In Fig. 2, we show an example of the catheter navigation process at the i_{th} step. Assuming that $(\mathbf{r}_c{}^t)_i$, is the true position of the catheter tip at the i_{th} step we calculate the body surface potentials due to the dipole at the catheter tip using the BEM and employ these potentials to estimate the position, $(\mathbf{r}_c{}^e)_i$, and orientation of the dipole at the tip of the catheter using our inverse algorithm. Then, we calculate the distance $(d\mathbf{r})_i$ between the target site, $\mathbf{r}_t$, and the estimated position of the tip of the catheter. In the next step, $(\mathbf{r}_c{}^t)_{i+1}$, the position of the tip of the catheter is adjusted (moved towards the target) by moving the dipole at the tip of the catheter $|(d\mathbf{r})_i|$ towards the target, while the dipole at the catheter tip is rotated to have



(a) The triangular description of the torso (left) and 49 (out of 64) electrode positions on the torso model (right).



(b) The triangular descriptions of the heart and lungs in the model. Front view (the right side of the figure corresponds to the left side of the body).

Fig. 1. The realistic anatomical geometry model used in the BEM.

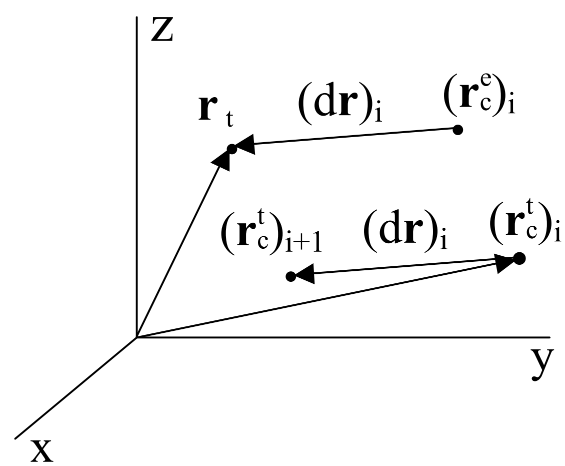


Fig. 2. Representative example of the catheter navigation (i_{th} step). Here, $(\mathbf{r}_c{}^t)_i$, is the true position of the catheter tip at the i_{th} step; $(\mathbf{r}_c{}^e)_i$, is the estimated position of the catheter tip at the i_{th} step; $(d\mathbf{r})_i$, is the distance between the target site ($\mathbf{r}_t$,) and the estimated position of the tip of the catheter $(\mathbf{r}_c{}^e)_i$; $(\mathbf{r}_c{}^t)_{i+1}$, is the position of the tip of the catheter at the $(i+1)_{th}$ step resulting by moving the dipole at the estimated position of the tip of the catheter a distance $|(d\mathbf{r})_i|$ towards the target.

similar orientation with that of the target dipole obtained using the inverse algorithm. These steps are repeated until the distance of the tip of the catheter from the true target position becomes smaller than 1 mm. The true target position is chosen to stop a trial because one of the purposes of this simulation is to examine the effectiveness of the inverse algorithm to accurately navigate the tip of the catheter to the target position. Ten trials resulting from different initial points towards the same target were carried out.

III. Results

Fig. 3 illustrates an example of the trajectory of the tip of the catheter in the heart. In this example, the initial distance between the target dipole and the catheter tip in the ventricle was 64.1 mm and it took 5 iterations to reach the final catheter position, which was 0.8 mm apart from the target. Table I shows the individual components of the average and standard deviation of the final position of the tip of the catheter over ten trials. We found that the overall average and standard deviation of the distance between the final catheter position and the target position was 0.74 ± 0.20 mm. On average, it took 6.9 iterations to reach the final catheter position. The minimum and maximum number of iterations were 4 and 11, respectively. The distance of the position of the tip of the catheter from the target position at the beginning of the simulation ranged between 24.7 mm and 65.5 mm. The distance between the final position of the tip and the target position ranged between 0.4 mm and 0.9 mm. These results demonstrated that the systematic error alone had minor influence in the catheter navigation towards the site of the origin of the arrhythmia.

IV. Summary

In this study, we employed computer simulations to investigate the accuracy of an algorithm to guide the ablative therapy of cardiac arrhythmias. In these simulations, we attempted to reproduce the catheter navigation process followed in a clinical procedure to examine the ability of this algorithm to accurately guide the tip of the ablation catheter to the site of the origin of the arrhythmia. The simulation results indicated that the effect of the systematic error in the ability of the inverse algorithm to identify the SEMD parameters and guide the catheter navigation was minor. Furthermore, one of the potential merits of this navigation method is that it does not require fluoroscopic guidance to guide the tip of the catheter to the site of the origin of the arrhythmia.

In future research, we aim to study the effect of measurement noise, target position, number and position of electrodes in the catheter navigation.

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TABLE I
THE TARGET POSITION AND THE AVERAGE DISTANCE OF THE FINAL CATHETER POSITION OVER TEN TRIALS.

	X (mm)	Y (mm)	Z (mm)
Target position	5.03	69.53	40.03
Final catheter position	5.10±0.29	69.31±0.60	39.76±0.24

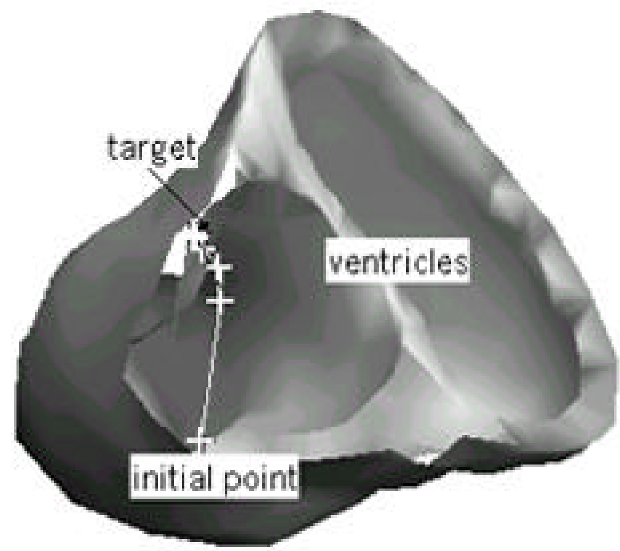

Fig. 3. Representative example of the trajectory of the catheter tip in the heart. A white '+' mark denotes the position of the catheter tip in each step. The initial and final distances were 64.1 mm and 0.8 mm, respectively.

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